

Visual and Thermal Performance of Natural and Artificial Luminaires

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Abstract: Using light pipe technology as a daylighting strategy offers considerable advantages because daylight can be transmitted virtually to any space inside the building. Its simple structure is an additional advantage as it is aesthetically acceptable and harmonizes with building environment. Switching to daylighting for interior lighting during daytime means great saving in total electricity consumption in buildings as well as good long-term money saving to consumers. This paper reports on the visual and thermal performance inside a test room, in particular under tropical climatic conditions, due to different lighting systems. The measurements of illuminance level and air temperature for both indoor and outdoor were carried out simultaneously over a certain period of time. For comparison purposes the study was divided to three cases, which were categorized by different lighting strategies or luminaires used inside the test room. In the first case, the room was totally illuminated by natural daylight from a light pipe, while in the second case, illumination was provided by artificial lighting using two 36W-fluorescent lamps. In the final part, the same measurements were made when the room was illuminated by daylight from window openings. In all three cases, measurements were carried out continuously from 7:30 hrs to 18:30 hrs. It was found that the light pipe performed best in terms of visual quality and thermal impact inside the test room.

Keywords: Light pipe, indoor visual and thermal environment, illuminance, tropical climates

1. INTRODUCTION

The excessive use of electricity can lead to global warming associated with high levels of greenhouse gas emission besides escalating cost of living. As in 2003, the use of electric lighting during daytime in tropical regions contributed to about 40% of the overall use of energy in buildings. It is predicted that in the year 2010, electricity peak demand in Malaysia is projected to grow by more than 117% [1-2]. While electric lighting is obviously necessary after sundown, very often energy is wasted by its use during the day. This is usually the result of poor building design and/or lack of windows [3].

The visual spectrum of the solar radiation is actually the best source of natural lighting and careful use of this renewable source can reduce the dependence on electrical lighting [4]. Meanwhile, the main factors that affect thermal comfort in tropical regions are solar radiation, temperature and humidity. Achieving indoor thermal comfort in humid tropical climates is more difficult due to the combined effects of high temperatures and humidity but cooling effects of indoor airflow from prevailing breezes is the principal technique used [5]. To handle the issues, a passive design strategy that can improve interior lighting conditions without compromising thermal comfort using natural measures would be an ideal solution.

Light pipes are said to be able to capture, reflect and transmit daylight into the interior space without creating excessive glare and heat gain problems. In some countries, light pipes have been widely used to bring in natural daylight into buildings, underground spaces and tunnels. However, in tropical countries, using openings like doors and windows are still considered as a primary method to bring in daylight into buildings especially in homes and residences. Otherwise, electric lighting and air-conditioning system would be the option especially when daylight is found insufficient.

A study was conducted to compare the visual and thermal performance of three indoor lighting strategies, which include the use of electrical lighting, light pipe and openings. Knowledge on the performance of these luminaires will create a greater awareness among consumers and society as a whole. The results would also be used as part of the study that is being carried out to develop an integrated daylighting and natural ventilation systems for the tropics.

2. METHODOLOGY

A light pipe of diameter 27 cm and length 130 cm was installed in a test room of floor size 4.5 m x 4.5 m and height 3.05 m. The room, which was painted white has one door and two windows on

perpendicular walls with opening area equivalent to 10% of the floor area as required by the Malaysian Uniform Buildings By Law [6]. The light pipe was located approximately at the centre of the room's ceiling.

The work was divided into two major parts. The first part was the measurements on thermal performance whereas in the second part measurements were carried out on visual performance. Each part was then subdivided into three cases. In the first case, all openings were shut and covered and the electric lighting was switched off. Therefore, the test room was totally illuminated by natural daylight from the light pipe. In the second case, all openings and also the light pipe were covered. The illumination for the test room was provided using two fluorescent lamps of 36 W each. In the third case, measurements were carried out with the room illuminated only by the natural daylight from windows. In all cases, the measurements were taken when the room was unoccupied and empty with no heat-generating device present inside the room. The experiment was carried out in March 2005.

2.1 Measurements of thermal performance

Measurements of relative humidity and air temperature were taken using Lastem Sensors connected to a data logger which is able to record data automatically over a period of time. The data was then transferred to a computer using a software called Dewesoft. All calculation was done using Microsoft Excell Software. The outdoor climatic parameters were measured and recorded continuously using Symphonie data logger. The sensors for measuring the outdoor data were placed at a height of one meter above the rooftop whereas for the indoor, all sensors were placed at work level, that is 0.75 m above the floor. Interior measurements were taken every minute, while outdoor measurements every 10 minutes for the period between 7:00 hrs and 19:00 hrs.

2.2 Measurements of visual performance

The room floor was divided into 7 x 7 grids with each division measures an area of 0.5 m x 0.5 m. The measurement was taken during the period between 11:00 hrs to 13:00 hrs when the position of the sun is close to zenith, using the same data logger as in the previous part together with Lastem C502LUX detectors. The detectors were always placed at a height of reading level, which is 0.75 m above the floor. The illuminance levels, outdoor and indoor were carefully measured simultaneously in order to determine and to observe the daylight factors distribution inside a test cell where the skylight was installed. The daylight factor (DF) is defined as the fraction of the interior illuminance over the exterior illuminance and is normally expressed in percentage:

$$\text{Daylight Factor (DF)} = \frac{\text{Interior illuminance}}{\text{Exterior illuminance}} \times 100\% \quad (1)$$

From the daylight factors, the interior illuminance could be established for any value of the exterior illuminance [7]. In calculating the interior illuminance at different solar times, the average hourly

illuminance taken from Model Year Climate Data for Klang Valley, Malaysia was used.

3. RESULTS AND DISCUSSION

3.1 Analysis on Thermal Performance

The measurements for the three cases were taken on different days but within the same month. However, the indoor and outdoor air temperature and humidity were measured simultaneously. The values of air temperature and relative humidity shown in Table 1 below are the hourly average values. The experiments were conducted in the month of March, the hottest month of the year in Malaysia. It is portrayed from the high values of outdoor temperature and relatively low humidity during the daytime.

Table 1: Indoor and Outdoor Average Temperature and Humidity From Different Luminaries

Time (hr)	Indoor Temp (°C)	Outdoor Temp (°C)	Indoor Humidity (%RH)	Outdoor Humidity (%RH)
Case 1: Light pipe				
8:30	29.6	29.7	60.2	50.7
10:30	30.0	33.2	55.7	49.9
12:30	30.7	35.9	52.8	48.0
14:30	31.7	38.0	49.7	47.0
16:30	32.7	35.1	47.0	49.0
18:30	32.3	29.8	55.0	50.8
Case 2: Electric Lamps				
8:30	28.7	28.1	67.8	47.5
10:30	28.6	31.5	51.3	46.3
12:30	29.4	34.5	48.5	44.9
14:30	30.4	36.5	45.5	43.5
16:30	31.2	33.9	43.7	45.0
18:30	31.1	29.7	53.0	46.2
Case 3: Openings (windows)				
8:30	28.9	29.7	63.7	49.1
10:30	30.2	33.3	53.4	47.5
12:30	31.8	37.5	48.6	46.4
14:30	32.4	36.0	51.1	47.0
16:30	32.8	36.1	52.1	47.0
18:30	29.7	30.5	54.8	49.0

Since the measurements were taken on different days it is more meaningful to observe the differences in the temperature and humidity between the outdoor and indoor rather than the true values. The values of the differences are shown in Tables 2 and 3 below. The temperature differences were determined using the expression;

$$\text{Temp. Diff.} = T_{\text{outdoor}} - T_{\text{indoor}} \quad (2)$$

whereas for the humidity, it is according to the equation;

$$\text{Humidity Diff.} = \text{Hum}_{\text{outdoor}} - \text{Hum}_{\text{indoor}} \quad (3)$$

Table 2: Indoor-outdoor Temperature Differences From Difference Luminaires

Time (hr)	Case 1: Using Light Pipe (°C)	Case 2: Using Electric Lamps (°C)	Case 3: Using Windows (Opening) (°C)
8:30	0.1	-0.6	0.8
10:30	3.2	2.9	3.1
12:30	5.2	5.1	5.7
14:30	6.3	6.1	3.6
16:30	2.4	2.7	3.3
18:30	-2.5	-1.4	0.8

It was found that the indoor air temperature was slightly lower when the room was illuminated by the natural daylight from light pipe compared to the artificial light. This is indicated by the larger values of indoor-outdoor temperature differences for Case 1. The graphical representation of the differences is shown in Fig. 1 below. It could also be observed that the natural daylight from windows shows the same thermal performance in the morning as the other two luminaires, however the effect has drastically changed after 12:00 o'clock in the afternoon. That could be explained from the fact that the windows are located on two perpendicular walls, which are facing South West and North West. This means that in the late afternoon, the sunlight would directly enter the room through the windows, which at the same time serve as an entrance for heat.

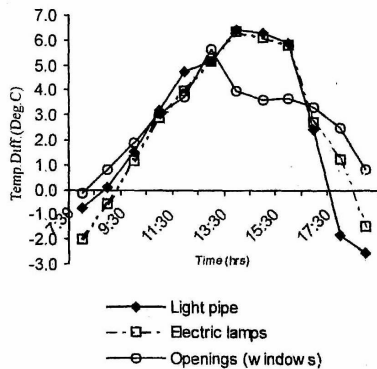


Figure 1: Graph of Temperature Differences Vs Time Due to Different Luminaires.

For the case of humidity, the indoor-outdoor differences were found slightly lower in case 2, in which situation the room was totally illuminated by electric lighting. Based on Eqn. 3, it should be clear that the high negative values shown in Table 3 below means the indoor humidity was relatively lower among the three illumination strategies. The results show that air humidity decreases as the temperature increases. This fact is supported from the graphs plotted in Fig. 2 below where the relationship between the air temperature and relative humidity for Case 1 are shown. Although the graphs were plotted particularly based on Case 1, the measured data for Cases 2 and 3 also indicate the same scenario. However, the values vary for different luminaires as summarized in Table 3.

Table 3: Indoor-outdoor Humidity Difference From Difference Luminaires

Time	From Light Pipe (% RH)	From Electric Lamps (% RH)	From Windows (Opening) (% RH)
8:30	-9.4	-20.3	-14.6
10:30	-5.8	-5.0	-5.9
12:30	-4.8	-3.6	-2.2
14:30	-2.7	-2.0	-4.1
16:30	2.0	1.3	-5.1
18:30	-4.2	-6.8	-5.8

—□— Indoor Temp. —×— Outdoor Temp.
—○— Indoor RH —◆— Outdoor RH

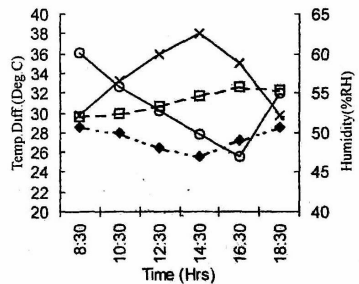


Figure 2: Graph of Relative Humidity and Temperature Vs Time For Case 1.

3.2 Analysis on Visual Performance

The distribution of DF values for cases 1 and 3, where the room were illuminated by natural daylight are presented graphically in Fig. 3 and 4. The light is not well distributed throughout the room where the high values of daylight factors for case 1 are concentrated within the area directly below the light pipe, whereas in case 3, the concentration was found in the regions close to the windows, as expected.

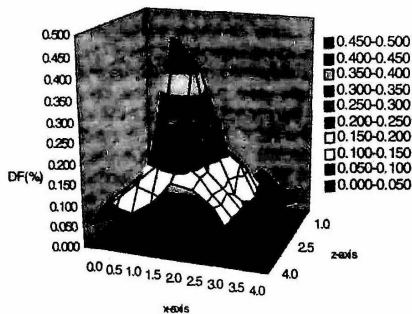


Figure 3: Daylight Factor (DF) Distribution Pattern Inside the Test Room Due to Light Pipe (Case 1)

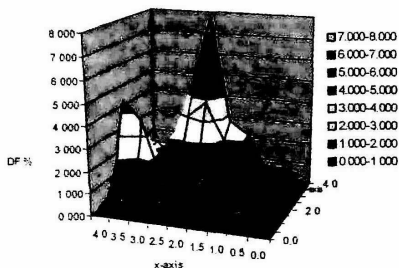


Figure 4: Daylight Factor (DF) Distribution Pattern Inside the Test Room Due to Windows (Case 2)

Tables 4 and 5 below show the interior illuminance inside the test room based on the value of external illuminance 70,000 lx. That is based on the fact the mean illuminance occurs in the month of June whilst the hottest and the coolest months are March and December, respectively. In case 1, the room illumination is not sufficient for reading and working. The recommended illuminance level for reading and writing is 350 lx^[6]. However in case 2 the illuminance levels are relatively high. It shows that openings are effective to bring in light into the interior space. Unfortunately, results from the previous part of the study have shown that it also brings in heat.

Table 4: Daylight Distribution in Lux Due To Light Pipe at 12:00 noon in June

X(m) Y(m)	0.5	1.0	1.5	2.0	2.5	3.0	3.5
0.5	56.4	80.9	112.8	144.2	156.3	129.9	61.5
1.0	58.5	80.9	118.7	199.4	203.1	128.2	58.1
1.5	54.1	76.8	110.5	333.5	296.8	160.4	55.0
2.0	48.1	72.7	100.8	320.1	280.6	152.3	54.2
2.5	41.0	56.2	85.3	146.0	132.9	134.6	48.2
3.0	38.2	52.9	83.3	79.3	78.4	63.4	37.0
3.5	28.7	40.3	52.6	66.9	61.0	38.1	28.9

Table 5: Daylight Distribution in Lux Due To Windows at 12:00 noon in June

X(m) Y(m)	0.5	1.0	1.5	2.0	2.5	3.0	3.5
0.5	1490	3137	2230	505	473	519	441
1.0	1347	1881	1480	713	863	1082	1233
1.5	723	1324	1267	709	847	1141	2409
2.0	345	522	837	739	960	997	2033
2.5	265	543	594	548	744	848	1391
3.0	189	333	354	396	724	463	535
3.5	222	502	524	362	664	264	174

For the purpose of comparing the lighting performance for all three cases, the average Daylight Factors (DF) were calculated by taking into consideration a few points on the work level plane around the centre of the test room. Simultaneously, measurement on illuminance due to artificial light at the same point shows a value of 298.3 lx.

Table 6: Average Values of Daylight Factors Inside the Occupied Space

	Light pipe	Openings (Windows)
Average DF(%)	0.4396	0.7579

From the average values of DF, the average interior illuminance at different solar times was calculated. Fig. 5 shows illuminance level around the centre of the floor. In terms of illuminance level, it is obvious that openings gave the best performance. The average illuminance level at 12:00 hrs reached a value of about 540 lx, which is excessive. Excess lighting also means excess solar energy impinging on the building walls and surfaces, overheating and glare⁽¹⁾. Although the lighting performance due to light pipe was below the standard, the illuminance level is still greater than the illumination from the artificial light when the external illuminance exceeds 68000 lx.

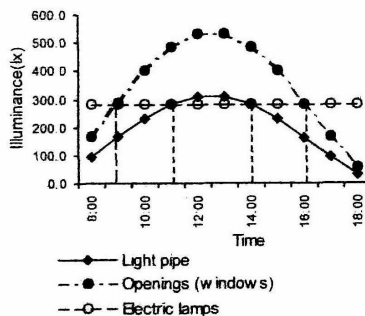


Figure 5: Graph of Average Interior Illuminance Level Vs. Time due to Different Luminaires.

It can also be visualized from Fig. 5 that, the interior illumination due to the natural light from the light pipe coincides with the illumination due to the electric lamps at around 11:30 hrs and 14:30 hrs. with the value of illuminance equals 298.3 lx. Therefore, comparison on the heat generated by both luminaires could further be investigated by referring to the indoor-outdoor temperature differences in Fig. 1 at those particular hours. The summary is shown in Table 6 below. It was found that, for the same amount of illuminance, the indoor-outdoor temperature differences due to the electric lamps were slightly lower compared to the case of the light pipe. Lower temperature difference means the true indoor temperature is high relative to the outdoor temperature. That indicates, the light from electric lamps generates more heat compared to the natural daylight due to the light pipe. The same investigations carried out on the natural daylight due to opening showed that the true indoor air temperature for Case 3 was always at the highest. That means, despite of introducing sufficient natural daylight into the interior space, openings at the same time have negative impacts on the indoor thermal comfort.

Table 7: Indoor-Outdoor Temperature Differences (°C) for Different Luminaires.

Time (Hrs)	$T_{out} - T_{in}$ (°C) (Light pipe)	$T_{out} - T_{in}$ (°C) (Electric Lamps)
11:30	4.7	4.0
14:30	6.3	6.1

4. CONCLUSION

The results of this study have shown that natural daylight from light pipe generates less heat compared to artificial light from electric lamps as well as the natural daylight from openings. It could be seen from the lower values of air temperature inside the occupied space when the room was illuminated using a light pipe. It was also found that the air humidity decreases with the rise of air temperature. As a consequence, a room illuminated by electric lamps was detected to be less humid. However, the differences in humidity for different cases were rather too small and almost negligible except during early in the morning. The results have also shown that the natural daylight due to openings caused the indoor air temperature to increase significantly.

In terms of the visual performance, openings were found to perform the best among the three luminaires between 9:30 hrs to 16:30 hrs. The transmitted illuminance was above 350 lx for about five hours per day. Light pipe was found to provide higher illumination than the electric lamps for three hours per day, i.e. between 11:30 hrs to 14:30 hrs. However, the illuminance transmitted was below the minimum value required for reading and working,

which is 350 lx. The illuminance due to electric lighting was constant at 298.3 lx, which was also below the minimum value required.

In general, it could be concluded that the natural daylight from light pipe performs the best thermal performance for the indoor space, but the illuminance transmitted by the light pipe alone is insufficient for visual comfort. On the other hand, openings could be a reliable source of natural daylight, unfortunately it also becomes a source of heat. For a naturally ventilated building the presence of openings is a must to allow air movement and dehumidification, thus cannot be compromised. As a suggestion to address this problem is to use the light pipe incorporates with openings in a naturally ventilated building. However, the openings need to be carefully designed and located for optimum transmission of natural daylight and air ventilation, as well as reducing the heat gain. Depending on natural daylight during daytime would save the total energy consumption in a building by about 40% of the total energy consumption in a building.

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